

# Delaying the Catastrophic Arrival of the Brown Tree Snake to Hawaii

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## Abstract

This paper develops a two-stage model for the optimal management of a potential invasive species. The arrival of an invasive species is modeled as an irreversible event with an uncertain arrival time. The model is solved in two stages, beginning with the post-invasion stage. In this stage, we assume perfect certainty regarding population size and arrivals. The loss-minimizing paths of prevention and control are identified, resulting in a minimized present value penalty associated with the invasion. After calculating this penalty, we analyze the pre-invasion stage and solve for the level of prevention expenditures that will minimize expected total cost. For the case of the Brown Tree Snake potentially invading Hawaii, we find that under a regime of pre-commitment, pre-invasion expenditures on prevention should be approximately \$3.2 million today, decreasing every year until invasion. However, if the planner is permitted to re-evaluate the threat following a non-event, prevention will be lower (\$2.96 million a year) and constant until invasion. Once invasion occurs, optimal management requires lower annual expenditures on prevention (\$3.1 million) but requires \$1.6 million to be spent on control annually to keep the population at its steady state level.

**JEL Classification:** Q20, Q28, Q54, Q57

**Keywords:** catastrophe, hazard function, invasive species, Brown Tree Snake, *Boiga irregularis*, prevention and control, Hawaii

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## **1. Introduction**

The Brown Tree Snake accidentally arrived to Guam from Australia or New Guinea in military transport some time following World War II. The snake's presence was not seen as a major threat to the island until the early 1980's when densities of 100 snakes per hectare were recorded on certain parts of the island. Control efforts began soon after. Although densities have declined dramatically since then to an average of 10-20 snakes per hectare, damages persist in the form of power outages due to snakes on power lines, lost biodiversity (the snake extirpated 11 of 18 native forest birds on Guam), and medical visits from snakebites, mostly to young children.

Because of the high volume of transport between Guam and Hawaii, especially between military units, the snake poses a direct and immediate threat to Hawaii. There have already been 8 verified interceptions of the snake on the island of Oahu, all at ports of entry (Rodda et al. 1999).<sup>2</sup> Aside from these interceptions, there have been several credible sightings after which rapid response teams were deployed but no snake was captured, and several hundred snake sightings that were not confirmed as being a Brown Tree Snake.

It is widely believed that it is not a question of if, but when, the snake will arrive and establish in Hawaii. Furthermore, it is feared that once the snake is here it will be difficult to completely eradicate, due to the snake's cryptic nature and the associated high search cost. These characteristics motivate the model of invasion as an irreversible event of uncertain time, or catastrophe.

## **2. Methodology**

In the model, we assume that invasion happens only once. We define invasion as the arrival of enough snakes to form an incipient or self-sufficient population. For establishment to

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<sup>2</sup> Barbers Point Naval Air Station, Schofield Barracks, Honolulu International Airport, and Hickam Air Force Base

occur, these would likely need to arrive in the same location and at the same time. While it is possible that dispersed snakes that arrived in an independent time and location could eventually lead to establishment, the issues of age and spatial differentiation make this possibility highly unlikely.<sup>3</sup> Relatedly, while it is possible that more than the spark population of snakes could arrive at any one time, this probability is low enough such that we do not consider it here.

Because we assume an infinite time horizon, the invasion will happen, the uncertainty involves when it will occur. The objective is to optimally postpone the invasion, given a predetermined penalty associated with the arrival of the invasion. As invasion in this case is characterized by the arrival of enough snakes to be considered established, we assume away the possibility of a secular increase in snakes before establishment occurs.

We follow Tsur and Zemel (1998, 2004) and model invasion as an irreversible event with an uncertain arrival time. The invasion brings with it a penalty, and is governed by a hazard function, which is the probability that the invasion will occur given that it has not yet occurred. Knowler and Barbier (2005) follow a similar tack in their model of a private commercial plant breeding industry that imports an exotic plant species into a region. The risk associated with invasion is modeled using a probabilistic hazard function, the key determinants of which are the characteristics of the exotic plant and the number of commercial nurseries contributing to its dispersal. Their results suggest that the presence of a risk of invasion does not imply that it is socially optimal to prevent commercial sales of an exotic. They also derive assumptions under which no sales of the exotic are socially optimal.

The uncertain invasion time is denoted  $T$ . After  $T$  the model assumes perfect certainty, where the planner has perfect information regarding the snake population and the number of

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<sup>3</sup> Sexual maturation for BTS is thought to be reached at age 2-3, therefore the dispersed snakes would need to be at least this old to start reproducing (Rodda et al. 1999). Spatial differentiation is likely a more important concern, since the snakes may have arrived at different locations, and therefore must locate the other to begin populating.

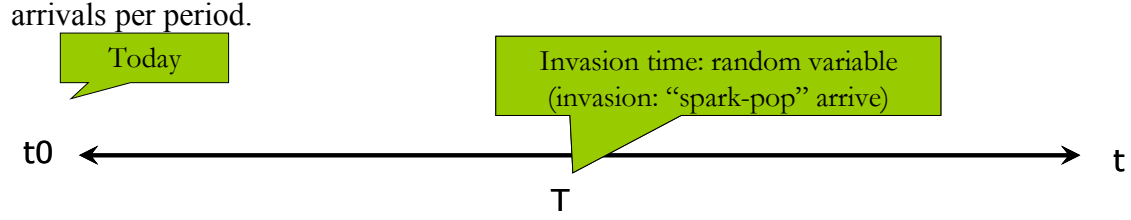


Figure 1. Timeline of Events

The model is solved in two stages: pre and post invasion. We begin with the post-invasion problem and solve for the optimal trajectories of prevention expenditures and removal to the steady state after invasion. The minimized total cost and damages  $\phi$  (or penalty) from the invasion are realized at (uncertain) time  $T$ .

### 3. Two-Part Model

#### 3.1 Post-invasion

For the sake of computational simplicity and clarity of exposition, we use a deterministic model to represent the state of the world post-invasion. Each period, the snake population is known and new entrants arrive on a continuous basis. The solution involves a steady state population of snakes and corresponding time paths of expenditures on avoidance and removals.

The problem is to:

$$\text{Max } V \text{ where } V = \int_0^{\infty} -e^{-rt} [c(n_t)x_t + D(n_t) + y_t] dt \quad (1)$$

subject to

$$\dot{n}_t = g(n_t) - x_t + f(y_t) \quad (2)$$

$$x_t \geq 0 \quad (3)$$

$$y_t \geq 0 \quad (4)$$

$$n_0 = n(0),$$

where  $n$  is the population of snakes,  $c$  is the unit cost of removal,  $D(n)$  is the damage function,  $y$  is avoidance expenditures,  $g(n)$  is the growth function,  $x$  is the harvest level and  $f(y)$  describes how many new snakes are added to the current population as a function of investment in avoidance.

The current value Hamiltonian for this problem is:

$$H = -c(n)x - D(n) - y + \lambda[g(n) - x + f(y)]$$

Application of the Maximum Principle leads to the following conditions:

$$\frac{\partial H}{\partial x} = -c(n) - \lambda \leq 0 \quad (5)$$

$$\frac{\partial H}{\partial y} = -1 + \lambda f'(y) \leq 0 \quad (6)$$

$$\frac{\partial H}{\partial n} = -c'(n)x - D'(n) + \lambda g'(n) = r\lambda - \dot{\lambda} \quad (7)$$

$$\frac{\partial H}{\partial \lambda} = g(n) - x + f(y) = \dot{n} \quad (8)$$

For all internal solutions, the following is true:

$$\lambda = -c(n) = \frac{1}{f'(y)} \quad (9)$$

Equation (9) states that at every period where there is positive spending on prevention and control, the marginal costs of each should equal to the shadow price of snakes. Since removal costs are linear with respect to  $x$ , a bang-bang solution is obtained whereby removal only occurs at the optimum steady state. Thus, if the population is less than the optimal steady state, prevention should be the only instrument employed until equation (6) holds with equality.

Because the focus of this paper is the pre-invasion model, details of the parameterization of the post-invasion model are provided in the appendix. The key finding from this model is the size of the penalty, which is \$239 million.

### 3.2 Pre-invasion

Beginning at time  $t_0$ , we spend  $y_t$  on prevention activities each period to postpone the invasion time  $T$ . We assume invasion happens only once, and has not yet occurred today at time  $t_0$ .

Random variable  $T$  has a continuous probability density function  $f(t)$ , where  $t$  is a realization of  $T$ .<sup>4</sup>

The cumulative probability is

$$F(t) = \int_0^t f(s)ds = \text{Prob}(T \leq t) \quad (10)$$

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<sup>4</sup> The following probability discussion and associated transformations are standard in the literature (see e.g., Kiefer 1988 and Greene 2000).

$F(t)$  specifies the probability that the invasion has occurred by time  $t$ . The upper tail area of the distribution is given by the survival function

$$S(t) = 1 - F(t) = \text{Prob}(T \geq t) \quad (11)$$

$S(t)$  specifies the probability that the invasion has not occurred by time  $t$ . Given that the invasion has not occurred at time  $t$ , the probability that it will occur in the next short interval of time, say  $\delta$ , is

$$\lambda(t, \delta) = \text{Prob}(t \leq T \leq t + \delta \mid T \geq t) \quad (12)$$

A useful function for characterizing this aspect of the distribution is the hazard rate,

$$h(t) = \lim_{\delta \rightarrow 0} \frac{\text{Prob}(t \leq T \leq t + \delta \mid T \geq t)}{\delta} \quad (13)$$

$$= \lim_{\delta \rightarrow 0} \frac{F(t + \delta) - F(t)}{\delta S(t)} \quad (14)$$

$$= \frac{f(t)}{S(t)} \quad (15)$$

Roughly,  $h(t)$  is the rate at which invasion will be completed at time  $t$ , given that it has not occurred before  $t$ . Because we assume the invasion happens only once and has not happened yet, the hazard rate will be useful in modeling the uncertain arrival of the BTS to Hawaii.

In our model we assume that invasion is not only a function of time, but also of how much managers invest in prevention activities. Therefore, our hazard rate will be a function of prevention expenditures  $y_t$ , and will be denoted  $h(y_t)$ .

We can use the integrated hazard function to write the expected value of losses given invasion at time  $T$ . First, note that

$$h(y_t) = \frac{-d \ln S(t)}{dt}, \quad (\text{since } \frac{-d \ln S(t)}{dt} = \frac{-d \ln(1 - F(t))}{dt} = \frac{f(t)}{1 - F(t)} = h(y_t)) \quad (16)$$

Define the integrated hazard function as

$$\Lambda(t) = \int_0^t h(y_\tau) d\tau \quad (17)$$

Using (16) above,

$$\Lambda(t) = \int_0^t \frac{-d \ln S(\tau)}{d\tau} \quad (18)$$

$$\Lambda(t) = -\ln S(t) - \ln S(0) \quad (19)$$

Because invasion has not yet occurred, survivorship at time 0 (today) is 1,

$$\Lambda(t) = -\ln S(t) - \ln 1 \quad (20)$$

Therefore,



$$\Lambda(t) = -\ln S(t) \quad (21)$$

$$e^{-\Lambda(t)} = S(t) \quad (22)$$

Thus

$$h(y_t) = \frac{f(t)}{S(t)} = \frac{f(t)}{e^{-\Lambda}} = \frac{f(t)}{e^{-\int_0^t h(y(\tau))d\tau}}, \quad (23)$$

and

$$f(t) = h(y_t) e^{-\int_0^t h(y(\tau))d\tau} \quad (24)$$

The pre-invasion problem is to:

$$\underset{y_t}{\text{Max}} \quad V \text{ where } V = \int_0^\infty h(y_t) S(u_t) \left\{ \int_0^T -y_t e^{-rt} dt - \phi e^{-rT} \right\} dT \quad (25)$$

Subject to

$$y_t \geq 0$$

Where  $y_t$  represents prevention investment at time  $t$ ,  $h(y_t)$  is the investment dependent hazard

rate,  $S(u_t)$  is the survival function, where  $u_t = \int_0^T h(y_t) dt$ , and  $\phi$  is the minimized penalty to be

realized upon invasion at time  $T$ . The stream of prevention expenditures are summed from time zero to the time of invasion, and the penalty  $\phi$  is discounted to time of realization  $T$ . The rate of discount is  $r$ .

Taking the derivative with respect to  $y_t$  and setting it equal to zero,

$$\frac{\partial V}{\partial y_t} = - \int_{t=T}^{\infty} h(y_t)S(y_T)e^{-rt}dT - \int_{t=T}^{\infty} \frac{\partial[h(y_t)S(y_T)]}{\partial y_t} \left[ \int_{t=0}^T y_t e^{-rt}dt + \phi e^{-rT} \right] dT = 0 \quad (26)$$

From (26), the first order condition is then

$$\underbrace{- \int_{t=T}^{\infty} h(y_T)S(T)e^{-rt}dT}_{\text{Expected cost of spending \$1 at time t}} - \underbrace{\int_{t=T}^{\infty} h(y_T)S_{y_t}(T) \left[ \int_{t=0}^T y_t e^{-rt}dt + \phi e^{-rT} \right] dT}_{\text{Cost of future losses (change in survival function)}} = \underbrace{h'(y_T)S(T) \left[ \int_{t=0}^T y_t e^{-rt}dt + \phi e^{-rT} \right]}_{\text{Benefit of spending today (change in hazard from spending now)}} \quad (27)$$

The two terms on the left hand side are the marginal costs of pre-invasion investment. The first term describes the expected cost of spending in time period  $t$ . The second component is the cost of future losses resulting from a change in the survival function, due to the fact that the invasion has not yet occurred. Although spending a dollar today decreases the likelihood of invasion today, the inevitability of invasion implies these avoided losses will be borne in the future. This term describes this increase in cost due to the change in the survival function ( $S_{y_t}$ ). Finally, the right hand side of equation (27) is the expression for the marginal benefit of pre-invasion spending. The change in the hazard rate as a result of spending today provides a benefit in future losses foregone.

## 4. Post-invasion Results

### 4.1 Pre-commitment of Prevention Funds

Parameterization of the above problem, using even the simplest of distributions, proved to be unwieldy and produced little insight into the question of optimal prevention investment over time. Therefore, we move to discrete time for the analysis of pre-invasion spending levels.

From the post-invasion modeling, under current annual prevention investments (\$2.6 million) the probability that one snake arrives in any given year is 20.6%. The pre-invasion model requires not one but two snakes to arrive together, and furthermore be in similar age cohorts, over 2-3 years old. These restrictive assumptions lead us to reduce the probability of this type of invasion to approximately 8%, given status quo levels of expenditures. Using this data, we estimate a hazard rate of

$$e^{-y_t/1.05} \quad (28)$$

where prevention investments  $y_t$  is in millions of dollars.

The problem is then to:

$$\underset{y_i}{\text{Max}} \quad W \text{ where } W = \sum_{T=0}^{\infty} e^{-y_T} e^{-\sum_{t=0}^{T-1} y_t} \left[ \sum_{t=0}^T y_i (1+r)^{-t} + \phi (1+r)^{-T} \right] \quad (29)$$

The first order condition to this optimization problem is:

$$\begin{aligned} \frac{\partial V}{\partial y_i} = & \left[ \sum_{i=1}^n e^{-y_i} \sum_{j=0}^{i-1} e^{y_j} (1+r)^{-i} \right] + e^{-y_i} \sum_{i=i+1}^n \left[ \left\{ \sum_{i=i+1}^n y_i (1+r)^{-i} + \phi (1+r)^{-i} \right\} * e^{-y_i} \sum_{j=0}^{i-1} e^{y_j} \right] \\ & - \left[ \left\{ \sum_{i=1}^i y_i (1+r)^{-i} + \phi (1+r)^{-i} \right\} * e^{-y_i} \sum_{j=0}^{i-1} e^{y_j} \right] = 0 \end{aligned} \quad (30)$$

Rearranging (30), we find that

$$\begin{aligned} & \underbrace{\left[ \sum_{i=1}^n e^{-y_i} \sum_{j=0}^{i-1} e^{y_j} (1+r)^{-i} \right]}_{\text{Marginal cost of spending}} + \underbrace{e^{-y_i} \sum_{i=i+1}^n \left[ \left\{ \sum_{i=i+1}^n y_i (1+r)^{-i} + \phi (1+r)^{-i} \right\} * e^{-y_i} \sum_{j=0}^{i-1} e^{y_j} \right]}_{\text{Marginal cost of spending now (increased probability of invasion later)}} = \\ & \underbrace{\left[ \left\{ \sum_{i=1}^i y_i (1+r)^{-i} + \phi (1+r)^{-i} \right\} * e^{-y_i} \sum_{j=0}^{i-1} e^{y_j} \right]}_{\text{Marginal benefit of spending now (reduced probability of invasion now)}} \end{aligned} \quad (31)$$

Using this hazard rate and the penalty of \$239 million from the post-invasion model, we find that optimal pre-invasion prevention should be approximately \$3.2 million today. These expenditures should decrease over time, since the inevitability of the invasion draws closer, represented formally by the survival function (that is, the “survival of the no invasion spell”) getting closer and closer to zero. Optimal prevention is illustrated for a 30-year time horizon in Figure 2 below.

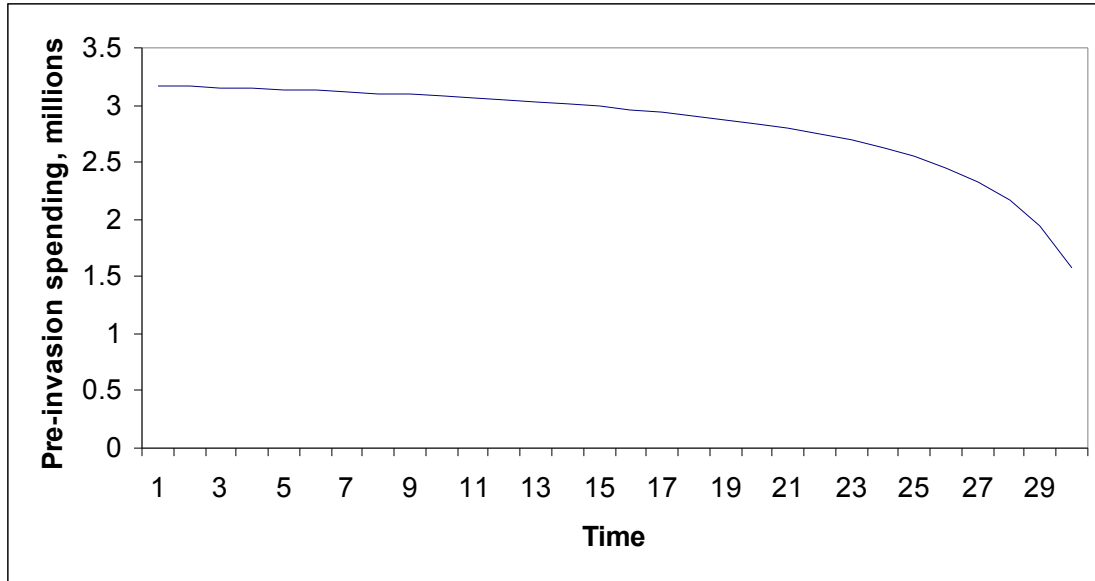


Figure 2. Optimal Pre-invasion Spending, 30-year Time Horizon

#### 4.2 Re-Evaluation of Prevention Funds

In any given period, if the invasion occurs, the manager or planner resorts to the paths of prevention and control as dictated by the deterministic model. The above analysis assumes that the planner has to make an *a priori* commitment of prevention funds over a specified time horizon. However, if the invasion does not occur in the current period, it is unlikely a planner would follow a schedule of decreasing prevention investments over time. Rather, the manager would reevaluate the problem and determine a new level of prevention, based on the absence of arrival. The problem the manager faces is exactly the same as before; as long as the invasion did not occur, the past expenditures on prevention do not influence the new optimal level of investment. Therefore, the solution to the problem will be exactly the same as in the previous period. Prevention expenditures are therefore constant in every period prior to invasion.

The problem will then be:

$$\underset{y}{Max} \ Z \text{ where } Z = \int_0^{\infty} h(y) e^{-h(y)T} \left\{ \frac{y}{r} (e^{-rT} - 1) - \phi e^{-rT} \right\} dT \quad (32)$$

The first order condition for this optimization problem is:

$$\underbrace{- \int_0^{\infty} h(y) * -h'(y) T e^{-h(y)T} \left\{ \frac{y}{r} (e^{-rT} - 1) - \phi e^{-rT} \right\} dT}_{\text{Marginal cost (when increase y 1 unit, probability happens later increases)}} - \underbrace{\int_0^{\infty} h(y) e^{-h(y)T} \left\{ \frac{1}{r} (e^{-rT} - 1) \right\} dT}_{\text{Marginal cost of spending}} =$$

$$\underbrace{\int_0^{\infty} h'(y) e^{-h(y)T} \left\{ \frac{y}{r} (e^{-rT} - 1) - \phi e^{-rT} \right\} dT}_{\text{Marginal benefit (when increase y 1 unit probability decreases)}}$$

(33)

Using the parameterization described above, we find that the optimal level of pre-invasion spending is \$2.96 million a year, for every year until invasion. Figure 3 below illustrates.

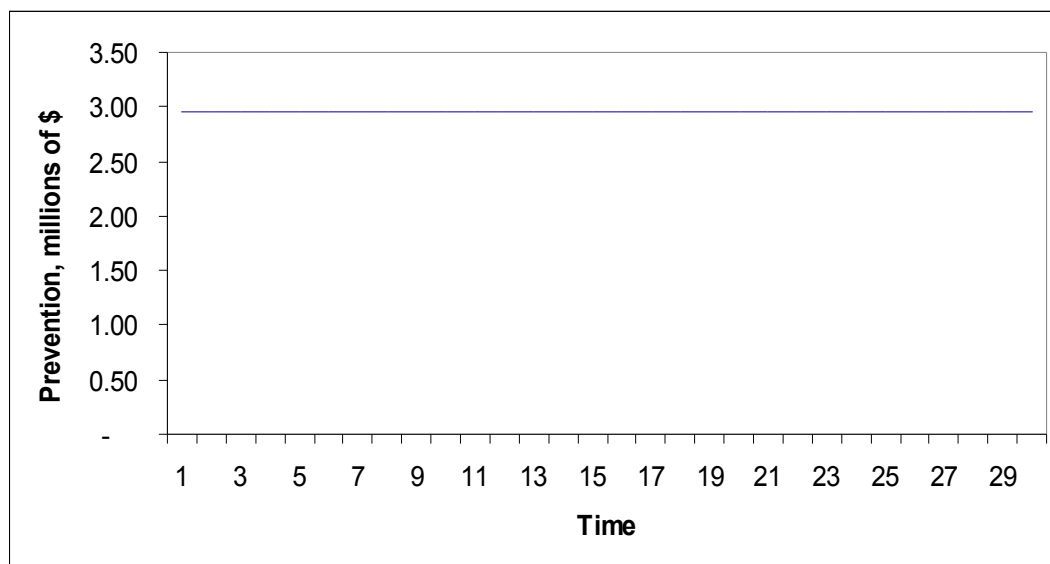


Figure 3. Constant Optimal Pre-invasion Spending, 30-year Time Horizon

An interesting result is that optimal prevention is higher under the explicit assumption of uncertainty regarding the time of invasion. This result has been shown many times in the area of environmental irreversibility (Arrow and Fisher 1974, Henry 1974, Kolstad 1996), in literature concerning the precautionary principle (Gollier et al. 2000, Gollier and Treich 2003) and in papers examining optimal capital stock levels under uncertainty (de la Croix and Licandro 1995, Abel and Eberly 1999, Mash 1999).

Arrow and Fisher (1974) and Henry (1974) demonstrated that, for a binary-choice or linear utility model, if there is uncertainty about the costs and benefits of a choice if one of the binary choices is irreversible, a decision maker would find it beneficial to err their decision away from the irreversible choice when there is a possibility of learning about the uncertainty in the future compared to the case when there is no future learning.

The precautionary principle has been analyzed in terms of the effect on rational decision-making of the interaction of irreversibility and uncertainty. Authors such as Epstein (1980) and

Arrow and Fischer (1974) show that irreversibility of possible future consequences creates a “quasi-option” effect which should induce a risk neutral society to favor current decisions that allow for more flexibility in the future (see also Fisher and Hanneman 1987). Gollier et al. (2000 p. 245) conclude that “more scientific uncertainty as to the distribution of a future risk — that is, a larger variability of beliefs — should induce society to take stronger prevention measures today.”

## **5. Comparative Static Results**

We also analyze the behavior of optimal prevention with respect to the hazard rate, discount rate, and size of the penalty.

### **5.1 Discount Rate**

Optimal prevention is found to be decreasing in the rate of discount. We find that under lower hazard rates, prevention will be lower than in the baseline case. However, for higher hazard rates, prevention can be above or below the baseline case. This is because for high enough hazard rates, prevention becomes ineffective, as the invasion becomes more likely to occur. Figure 4 below illustrates the relationship between prevention and discount rate for a range of hazard rates.



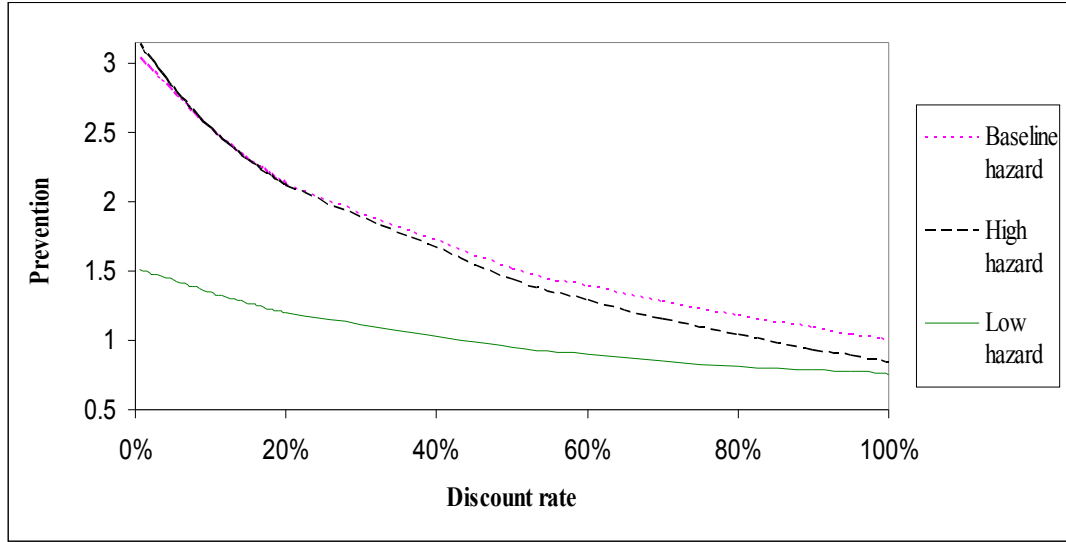


Figure 4. Relationship between Prevention and Discount Rate for Different Hazard Functions

## 5.2 Hazard Rates and the *Prevention Kuznets Curve*

We find the relationship between optimal prevention and the hazard rate to be approximately inverse-U shaped. This is because initially as the hazard rate increases, prevention becomes more worthwhile, but at high hazard magnitudes, prevention does less good than at lower hazard rates. This *Prevention Kuznets Curve* holds at all three penalty levels, with higher penalties requiring higher prevention and lower penalties requiring lower levels prevention in the optimal solution. Also note that the maximum prevention levels are increasing with level of penalty. Figure 5 illustrates the relationship between prevention and hazard rate for a range of penalties.

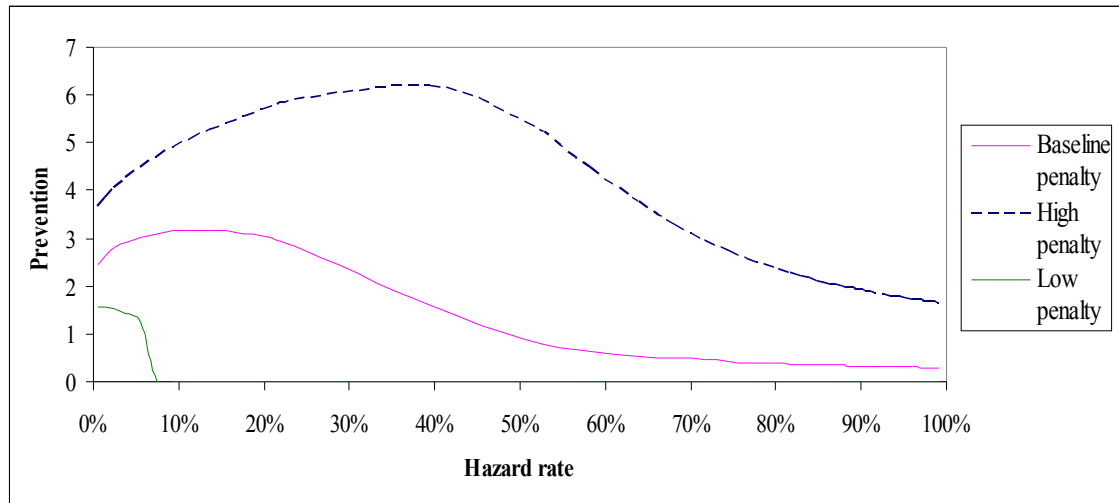


Figure 5. *Prevention Kuznets Curves* for Different Penalty Levels (2% discount rate)

### 5.3 Penalty

Finally, optimal prevention is found to be increasing in the size of the post-invasion penalty. The higher the cost of the invasion is, the higher the prevention in the optimal program.

Figure 6 illustrates for a range of hazard rates below.

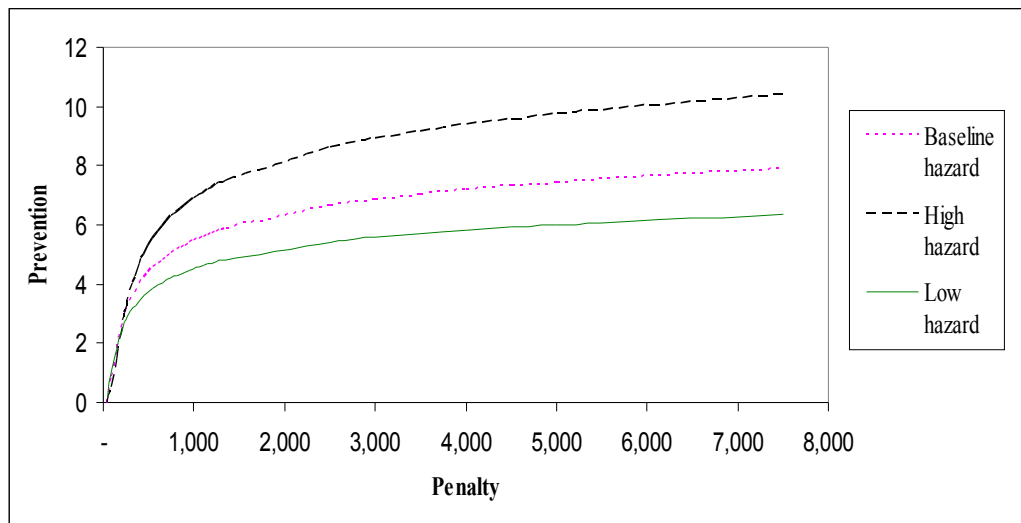


Figure 6. Relationship between Prevention and the Penalty for Different Hazard Levels (2% discount rate)

## 6. Conclusion

This paper develops a two-stage model for the optimal management of a potential invasive species. The arrival of the BTS is modeled as an irreversible event with an uncertain arrival time. The model is solved in two stages, beginning with the second stage, or post-invasion, identifying optimal management after the snake has invaded. In this second stage of the model, we assume perfect certainty regarding population size and arrivals. The loss-minimizing paths of prevention and control are identified, resulting in a minimized present value penalty associated with the invasion.

After calculating this penalty, we return to the first stage of the model, pre-invasion, and solve for the level of prevention expenditures that will minimize the total value of the invasion, pre and post-invasion. Here we assume that the time of invasion is unknown. Spending on prevention will delay but not avoid the arrival of the snake to Hawaii.

Using discrete time to characterize the invasion horizon, we find that if prevention investments are required to be pre-determined (closed-loop), expenditures made before the invasion should be decreasing over time. However, if the planner is allowed to re-evaluate the problem following a non-event (open-loop), optimal prevention investments will be constant. Regardless of whether or not the resource manager must pre-commit to a time path of prevention expenditures, prevention is increasing in the size of the post-invasion penalty and decreasing in the rate of discount. The relationship between efficient prevention and the hazard rate is found to be inverse U-shaped – a *prevention Kuznets* curve. As the hazard rate increases from zero, optimal prevention increases. But at high enough hazard rates, prevention expenditures become relatively ineffective compared to control. At some intermediate level, optimal prevention reaches a maximum and begins to decrease.

For the case of the BTS potentially invading Hawaii, we find that under a regime of pre-commitment, pre-invasion expenditures on prevention should be approximately \$3.2 million today and decrease every year until invasion. However, if the planner is permitted to re-evaluate the threat following a non-event, prevention will be lower (\$2.96 million a year) and constant until invasion. In both cases, incorporating uncertainty with respect to arrival time increases the efficient level of prevention expenditures in the current period, relative to the deterministic case. This result is in accordance with the literature on optimal-capital-stock-under-uncertainty and the precautionary principle.

Once invasion occurs, optimal management requires lower annual expenditures on prevention (\$3.1 million) but requires \$1.6 million to be spent on control annually to keep the population at its steady state level of two snakes. Prevention expenditures are found to be higher than those of control since by assumption there is no growth before the spark population is reached. Thus control expenditures are dedicated solely to removing the additional growth produced by the small population of snakes every year. Since growth is expensive to remove at low populations, the benefits of prevention are substantial. This result is sensitive to several parameters, including the cost of removal. If marginal control costs were higher at the steady state level, it is easy to imagine that control expenditures would be greater than prevention in the optimal program.

A possible extension of this model is to allow for continued uncertainty of arrivals after a viable population has been established. This may come at the cost of a large increase in complexity and loss of transparency however. Another possible extension that would involve dramatically more complexity would be to allow for stochastic establishment. Relatedly it would be useful to address considerations of age cohorts and spatial relationships of the individual pests. Finally, we have abstracted from the problem of uncertainty regarding the existing number

of pests at any given time and the relationship of an estimate thereof to search and removal efforts.

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## Appendix: Empirical Investigation, Post-invasion Model

### Growth Function

We utilize the following form of the logistic function,

$$g(n) = b(n - n_{\min}) \left( 1 - \frac{(n - n_{\min})}{n_{\max}} \right), \quad (\text{A1})$$

to represent the potential growth of the snakes. This is equivalent to a logistic growth function starting at  $n_{\min}$ . In this case, the intrinsic growth rate,  $b$ , is 0.6, based on estimated population densities at different time periods on Guam (Rodda et al. 1992 and personal communication 2005). The maximum elevation range of the snake may be as high as 1,400 m (Kraus and Cravalho 2001), which includes the entire island of Oahu. There are approximately 150,000 hectares of potential snake habitat on Oahu. Assuming a maximum population density of 50 snakes/hectare, carrying capacity ( $n_{\max}$ ) for the island of Oahu is 7,500,000.

Aside from integrated prevention and control, our model sets itself apart from current invasive species literature in one additional way. Unlike most bioeconomic models, where growth begins with the first individual, we assume a type of strong Allee effect (Stephens et al. 1999), with a minimum population level before which growth of the snake is not possible. For our case we assume this population ( $n_{\min}$ ) is two. It is possible that the minimum reproducible population could be much higher than two, given the size of the island and possible gender distributions. It is also possible that the minimum population is one, as female snakes are capable of (1) delaying birth for several months through “freezing” fertilized embryos and (2) parthenogenesis (BTS Technical Meeting, 2005). It is believed that the Guam population started from a single female (Rodda, pers. comm.). We use two here as a reasonable estimate that allows a clear examination of the tradeoffs when arrival and establishment are not interchangeable. Once this minimum or ‘spark’ population is reached the population grows along a logistic growth path.

### Damage Function

Major damages from BTS on Guam include lost productivity and repair costs due to power outages, medical costs from snakebites, and lost biodiversity from the extirpation of native bird species. Using data obtained from Guam, and positing a linear relationship between damages and number of snakes, we derive an equation for damages as a function of snakes.

$$D = 122.31 \cdot n_t. \quad (\text{A2})$$

For a more complete look at the derivation of this function, see Burnett (2007).

### Removal Cost Function

While to date there has yet to be a successful capture of BTS based on a credible sighting report or other search activities in Hawaii, we were able to obtain success rates for various capture techniques in an enclosure in Guam.<sup>5</sup> Using this data, we constructed a marginal cost function that is decreasing in  $n$ , but independent of  $x$ .

$$c(n) = \frac{1.547 * 10^7}{n^{0.8329}} \quad (A3)$$

For a more complete look at the derivation of this function, see Burnett (2007).

### Arrival Function

We assume that avoidance expenditures buy a reduction in the number of snakes that arrive and become established. According to our sources, under current avoidance expenditures of \$2.6 million, Oahu faces an approximate 90% probability that at least one snake will arrive over a ten-year time horizon. If expenditures increased to \$4.7 million, the probability of at least one arrival would decrease two-fold, to about 45% over the ten-year horizon. Finally, if we increase preventative spending to \$9 million per year, the probability of an arrival decreases another two-fold, to about 20%. We convert these probabilities to expected values using the Poisson distribution.

We then use the Weibull curve to fit the arrival function because of its flexible shape and ability to model a wide range of failure rates (e.g., in engineering, such as capacitor, ball bearing, relay and material strength failures). Here, the Weibull describes failure of the avoidance barrier. The resulting function is

$$\lambda(y) = \exp(2.3 - 0.00224y^{0.5}) \quad (A4)$$

### Optimal Avoidance and Removal Results

As mentioned previously, there is great uncertainty surrounding the present population of snakes in Hawaii, although the number is estimated to be between zero and 100. For this reason, we look at two cases. First, we determine optimal policy if there are no snakes in Hawaii, and second, we determine optimal policy given an initial population of 50 snakes.

Our analysis finds that the optimal strategy is to keep the local population to just under the minimum reproducible population. This is done through significant spending on prevention, followed by additional smaller expenditures on removals once the undetected arrivals reach the minimum reproducible population. Given our functional forms, if the current population is zero, then today it is optimal to spend \$2.94 million on avoidance only, an amount very close to what

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<sup>5</sup> There have been two recent combined attempts by state and federal agencies to catch snakes following single sighting events. One program was executed near Hana, Maui and the other in Kona, Hawaii. Each program lasted 3 weeks and entailed paying trained personnel overtime wages and flying specialized searchers out from Guam and the Northern Mariana Islands. Resource managers estimate each program to have cost around \$76,000.

authorities are currently spending today. With this level of spending, it takes about 10 years to reach  $n=2$ , at which point we begin removal expenditures to keep the population in a steady state. In the steady state, we spend \$3.2 million to keep all but 0.84 snakes from entering the island and \$1.6 million to remove 0.84 snakes every year. The steady state level of snakes is 2, and the present value of the optimal path (beginning with zero snakes) is \$223 million.